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THE EFFECT OF RESIN CONCENTRATION AND LAMINATING PRESSURES ON KEVLAR(R) FABRIC BONDED WITH A MODIFIED PHENOLIC RESIN

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Laminated Kevlar(R) panels, fabricated by high and low-pressure laminating techniques were evaluated to determine resistance to ballistic penetration, hardness, flexural modulus, and energy absorption. Compared with the high pressure laminates, low pressure panels made from the same material samples had greater resistance to ballistic penetration; in addition, they were softer, more flexible, and absorbed more flexural energy. The difference in performance characteristics is attributed to the adverse effects of resin impregnation down to the fiber level for the high-pressure panels as opposed to mere surface bonding of the fabric layers in the low-pressure laminations.

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PREFACE

The findings will support performance, processing, and fabrication of protective clothing and equipment made from rigid or semi-rigid laminated Kevlar(R) fabric structures. The authors wish to acknowledge the assistance provided by Ms. Nancy Fountain, Materials Research and Engineering Division, for the microscopy study that assisted in verifying the structures of the laminates, and to Mr. Frank Figucia, also of the Materials Research and Engineering Division, for his interest and supporting comments of the discussion of ballistic penetration.

US Customary units were used throughout this report to correspond to similar studies done by Natick R&D Center in the past.

TABLE OF CONTENTS

ILLUSTRATIVE DATA

TABLE		PAGE
1	Percent Resin Pick-Up of Coated Kevlar(R) Fabric and Percent Resin Content of Test Panels Fabricated from the Coated Kevlar(R) Fabric	3
2	Tangential Modulus of Elasticity and Energy Absorbed by Laminated Panels made from 9 Plies of Kevlar(R) Fabric Bonded with Different Resin Concentrations at High and Low Pressures	5
3	Tangential Modulus of Elasticity and Energy Absorbed by Laminated Panels made with 9, 10, 11, and 12 Plies of 19.8% Resin Content Kevlar(R) Fabric	7
4	Energy Absorbed by Kevlar(R) Fabric laminates Bonded at High and Low Pressures and with Similar Flexural Moduli	7
5	Hardness of Kevlar(R) Fabric Panels Laminated with High and Low Pressures	8
6	Ballistic Limit (V_{50}) of Laminated Panels Made from 9 Plies Kevlar(R) Fabric Bonded with Different Resin Concentrations at High and Low Pressures	10
7	Ballistic Limit (V_{50}) of Kevlar(R) Fabric Panels Bonded with Nominal 20 Percent Modified Phenolic Resin Content at High and Low Pressures	10
8	Properties of Kevlar(R) Fabric Panels Made by High and Low Laminating Pressures	11

THE EFFECT OF RESIN CONCENTRATION AND LAMINATING PRESSURES ON KEVLAR(R) FABRIC BONDED WITH A MODIFIED PHENOLIC RESIN

INTRODUCTION

During the early phases of the Vietnam encounter, the Army aircrew helmet was essentially comprised of a hard shell lined with a crushable expanded plastic. The shell was constructed from glass fabric bonded with a polyester resin; the liner was a rigid expanded polystyrene. This helmet provided an acceptable level of impact (crash) protection but no appreciable resistance to penetration by ballistic fragments.

An improved aircrew helmet could be provided, it was thought, by substituting a laminated nylon fabric shell for the glass fabric shell. The nylon fabric[1] had been used for the personal protective armored vest, and in the laminated form it had been used for the combat helmet liner and the Combat Vehicle Crew helmet[2] to impart ballistic resistance capabilities to the headgear.

Initial impact tests of laminated nylon fabric helmet shells yielded unacceptable results. The shell structure, with 15 to 18 percent resin content, appeared to absorb or dissipate low level impacts (kinetic energy of 160 foot-pounds delivered at a velocity of 25 feet per second). High speed motion pictures revealed excessive transient deformation* that caused bottoming.** When the rigidity of the shell structure was increased, it sustained greater impact forces without bottoming. A study was conducted to determine the effects of resin concentration on flexural modulus, energy absorption, and resistance to ballistic penetration of laminated nylon fabric.[3] Information developed in this study led to the development of the ballistic crash helmet used by Army aircrews in Vietnam.[4]

The development of Kevlar(R) introduced a new dimension into the design of flexible body armor. Utilizing Kevlar(R) fabric, lightweight, flexible, inconspicuous body armor that would withstand small arms projectiles became a reality.[5] With the advent of Kevlar(R)

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* Transient deformation is the deflection of a material that recovers when the load is removed. Transient deformation is a short duration phenomenon that usually cannot be detected visually.

** Bottoming is a phenomenon occurring during impact when input energy is transmitted to the sensing element with little or no attenuation.

fabric, the military gained increased fragmentation protection without weight penalty. Helmets made from laminated Kevlar(R) fabric confirmed projected characteristics predicated on the behavior of flexible and laminated nylon structures.

A previous study explored the effect of resin concentration on the properties of nylon laminates.[3] With the adoption of Kevlar(R), it was important to conduct a similar study of the effects of resin concentration upon its laminated structure.

Fabrication of Test Panels

Five rolls of untreated Kevlar(R) fabric[6] (14 oz per square yard) was balance-coated* with a catalyzed phenolic resin modified with a polyvinyl butyral resin. Each roll was coated with a different amount of resin. The rolls were cut into 12-inch by 12-inch pieces, weighed and stacked to form 9 to 12-layer units. Each of these stacked units were compression-molded at 325 to 330°F for 20 minutes in a 100-ton compression press, having 12-inch by 12-inch flat platens. Half of the units were molded at 1360 psi and half were molded at 400 psi. This procedure resulted in high and low-pressure laminated Kevlar(R) panels. These panels were measured for thickness and weight.

Resin Content (%) of the "B" stage** rolls and the "C" stage** panels were calculated as follows:

$$\% \text{ Resin Content} = \frac{(\text{mass of coated fabric or panel}) - (\text{mass of uncoated fabric})}{(\text{mass of coated fabric or panel})}$$

For this study the uncoated fabric was assumed to be homogeneous at 14 ± 0.5 oz per square yard. Table 1 lists the contractor's estimated resin content (%) of the 5 rolls of fabric, the calculated resin content (%) of the 5 rolls of fabric, and the calculated resin content (%) of high and low-pressure panels made from each of the rolls.

* A balance-coated fabric is a fabric that has an equal amount of resin compound on both sides.

** The resin monomer applied to a matrix is in the "A" stage. As a result of drying, it is partially cured or crosslinked and is in the "B" stage (green resin) when it may be formed; the resin will flow under heat and pressure. Continued heat and pressure will advance the polymerizing process to completion or "C" stage when the resin becomes a hard insoluble substance not softened by heat.

TABLE 1. Resin Content of Coated Kevlar(R) Fabrics and Laminated Panels Produced from the Fabric

Resin Content of Fabrics (Rolls)		Calculated Resin Content of Laminated Panels	
Contractor's Estimate (%)	Calculated (%)	High Pressure (%)	Low Pressure (%)
15.8	17.6	17.8	15.7
19.8	25.2	22.2	18.1
28.9	31.7	27.4	28.6
43.6	45.1	20.7	40.8
50.2	48.6	22.9	46.6

During the lamination process, it was observed that the high pressure caused resin to be excreted from the sides of the higher resin content fabric stacks. Fig. 1 and 2 show that 9-ply, high-pressure (1360-psi) laminates of Kevlar(R) fabrics were limited in resin content

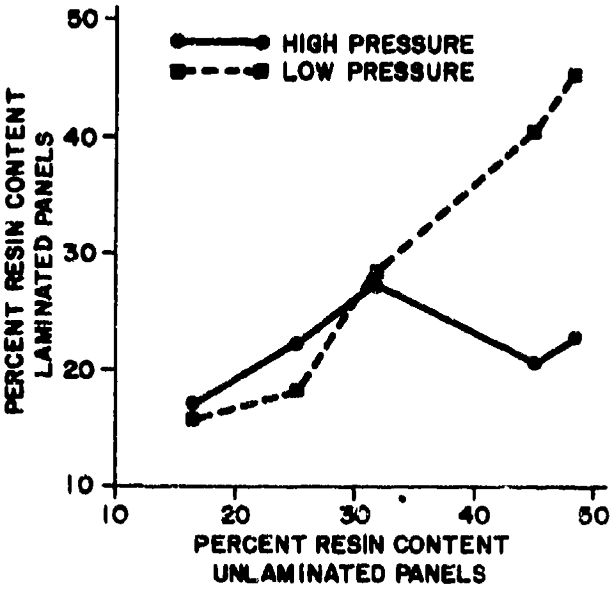

Figure 1. Resin content of 9 plies of Kevlar(R) fabric laminated as a function of laminating pressures.

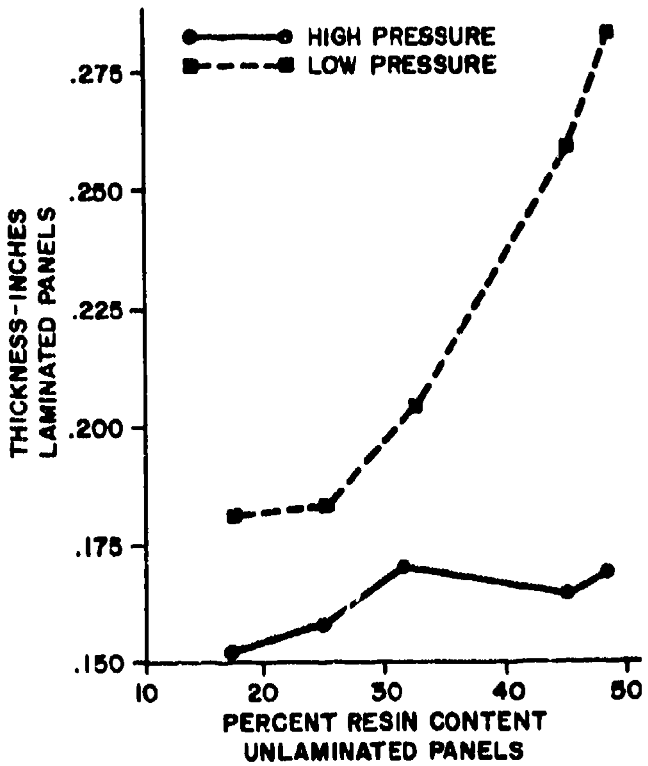

Figure 2. Thickness of 9 plies of Kevlar(R) fabric laminated as a function of resin content and pressure.

to about 27%, and limited in thickness to about 0.17 inches regardless of the resin content of the fabric. Fig. 1 and 2 also show that the thickness and resin content of the low-pressure (400-psi) laminates are proportional to the resin content of the fabric.

Seven nominally 1/2-inch by 6-inch specimens were cut from uniform sections near the periphery of each panel. Each specimen was weighed and measured. The remainder of each panel was used to determine ballistic penetration resistance.

Test Methods, Results, and Discussion

Three physical characteristics of the laminated panels were investigated: flexural modulus, energy absorption, and resistance to ballistic penetration. The hardness of the laminates was also measured.

Flexural modulus (tangential modulus of elasticity) of each test specimen was determined by center beam loading using a 4-inch span.[7] Each specimen was loaded at a rate of 5 inches per minute to a deflection of 0.75 inch and unloaded at the same rate. Table 2 shows that laminating pressure is the overriding factor in stiffness determination. It has been commonly accepted that decreased thickness of a material would make it more flexible, and greater solvent retention would act as a plasticizer and reinforce this flexibility. The high-pressure laminates, however, are stiffer than the low-pressure laminates, although they are thinner and retain more volatiles.

TABLE 2. Tangential Modulus of Elasticity and Energy Absorbed by 9-Ply Laminated Panels with Differing Resin Concentrations at High and Low Pressures

Contractor's Estimated Fabric Content (%)	High Pressure Laminate: Resin Content (%)	Flex. Mod. x 10^5 psi	Energy Absorbed in.-lb/in.^{2}	Low Pressure Laminate: Resin Content (%)	Flex. Mod. x 10^5 psi	Energy Absorbed in.-lb/in.^{2}
15.8	17.8	12.32	84.5	15.7	7.10	44.5
19.8	20.3	11.01	88.9	18.4	7.63	83.6
28.9	27.4	25.60	214.9	28.6	12.37	158.2
43.6	20.7	24.13	183.9	40.8	10.38	429.8
50.2	22.9	27.14	207.6	46.6	12.23	541.9

Small increases in resin content greatly increased the stiffness of the high-pressure laminates, as opposed to the tendency of low-pressure laminates to remain flexible. Fig. 3 indicates that with greater than 30 percent resin content, the flexural modulus of the low-pressure laminate rises asymptotically to a limit of approximately 12 x 10^5 psi, as the resin content increases. The flexural modulus of the high pressure laminates increases steeply with increased resin content.

The energy absorbed by each sample as a result of the flexural modulus determination was calculated from the area of the hysteresis loop, formed during the loading and unloading of the test specimen. Table 2 shows that the energy absorbed by the high and low-pressure laminates is related to their resin content and flexural modulus. Both high and low-pressure laminates exhibit an increased capacity to absorb energy as the resin content increases.

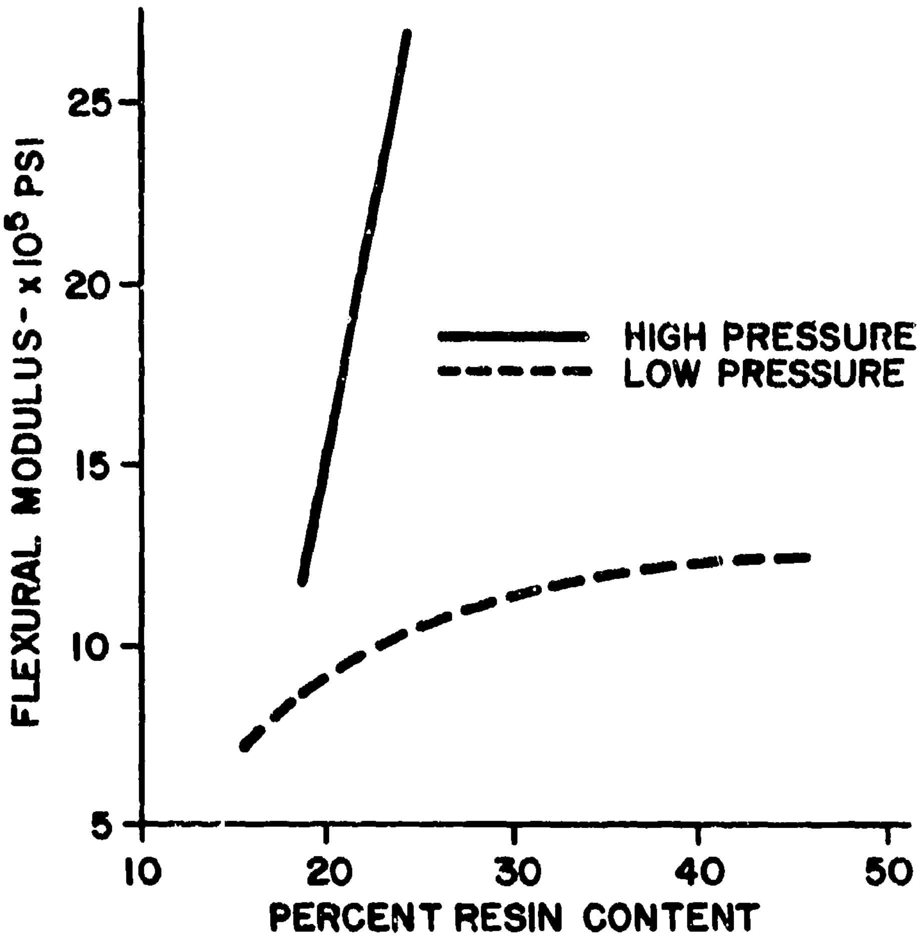

Figure 3. Flexural modulus of laminated Kevlar(R) fabric as a function of resin content.

Laminated panels with 9 to 12 plies from the 19.8% resin content fabric showed no significant difference in stiffness within its laminating pressure series (Table 3). The stiffness of the high-pressure panels exhibited a greater degree of variability than did the low-pressure panels. The energy absorbed by each panel increased with the addition of each layer.

Notwithstanding the different resin content, Table 4 shows that of the panels with equivalent flexural moduli, the low pressure laminates absorb significantly more energy than do the high pressure laminates.

TABLE 3. Tangential Modulus of Elasticity and Energy Absorbed by Laminated Panels made with 9, 10, 11, and 12 Plies of 19.8% Resin Content Kevlar(R) Fabric

No. Plies	High Pressure Laminate			Low Pressure Laminate		
	Flexural Mod.		Energy	Flexural Mod.		Energy
	$\times 10^5$ psi	S.D.*	in.-lb/in.^{2}	$\times 10^5$ psi	S.D.*	in.-lb/in.^{2}
9	11.01	1.94	88.9	7.63	0.40	83.6
10	10.84	2.15	105.5	7.66	0.60	94.1
11	12.31	1.80	125.2	8.17	0.41	109.7
12	9.52	2.45	130.4	7.96	0.53	128.0

*Standard Deviation

TABLE 4. Energy Absorbed by Kevlar(R) Fabric Laminates Bonded at High and Low Pressures and with Similar Flexural Moduli

Contractor's Estimated Fabric Resin Content (%)	Calculated Resin Content (%)	Thickness (in.)	Flex.Mod. $\times 10^5$ psi	Energy Absorbed in.-lb/in.^{2}
15.8	17.8 (H)	0.152	12.32	84.5
28.9	28.6 (L)	0.204	12.37	158.2
50.2	46.6 (L)	0.283	12.23	541.9

(H) High-Pressure Lamination
(L) Low-Pressure Lamination

Thickness of the panel correlates with the energy absorbed but does not appear to influence the panel's stiffness. The Kevlar(R) laminates do not adhere to accepted principles that stiffness increases with thickness and energy absorption increases with flexural modulus. The laminated panels are orthotropic homogeneous composites, that is, a uniform fabric and resin structure in two directions only.

Input energy during center beam loading will be absorbed or dissipated by several mechanisms - extension, compression, fracture, delamination, and friction — as well as heat that may be generated. These mechanisms appear to react differently with each fabrication method; this may be attributed to the resulting structure of the laminate. The high pressure and heat of the high pressure laminations caused the resin to flow and penetrate through the yarns, thereby encapsulating fibers; this impregnation formed a hard dense concretion. The low pressure laminate, however, is formed by bonding the surfaces of each layer of fabric to its adjacent plies, see Figure 4.

Table 5 compares the hardness of high and low pressure laminated Kevlar(R) fabric panels using the Rockwell (L) scale.[8]

TABLE 5. Hardness of Kevlar(R) Fabric Panels Laminated with High and Low Pressures

Contractor's Estimated Fabric Resin Content (%)	High Pressure Resin Content (%)	High Pressure Hardness Rockwell(L)	Low Pressure Resin Content (%)	Low Pressure Hardness Rockwell(L)
15.8	17.8	85.5	15.7	19.6
19.8	22.2	74.4	18.1	27.1
28.9	27.4	104.2	28.6	55.4
43.6	20.7	103.2	40.8	50.4
50.2	22.9	103.6	46.6	72.4

The hardness of the laminates appears to correlate well with their flexural moduli. For the same resin content, the high pressure laminates are harder than the low pressure panels.

Laminated Kevlar(R) fabric is used for the military combat helmet because of its superior resistance to penetration of ballistic missiles. Thus, throughout the study, the properties of the test panels were related to their effect on ballistic resistance. No known studies were made of the effects of high and low-pressure laminating on the ballistic resistance characteristics of nylon fabric laminates. The liner for the M-1 combat helmet and the Combat Vehicle Crew (CVC) Helmet[2] were made from 4 and 9 layers of nylon fabric, respectively, bonded with a modified phenolic resin similar to that used for the Kevlar(R) test panels. The M-1 helmet liner was produced by a high-pressure molding technique and the CVC Helmet shell was fabricated by a low-pressure method. The initial resin concentration of the structure

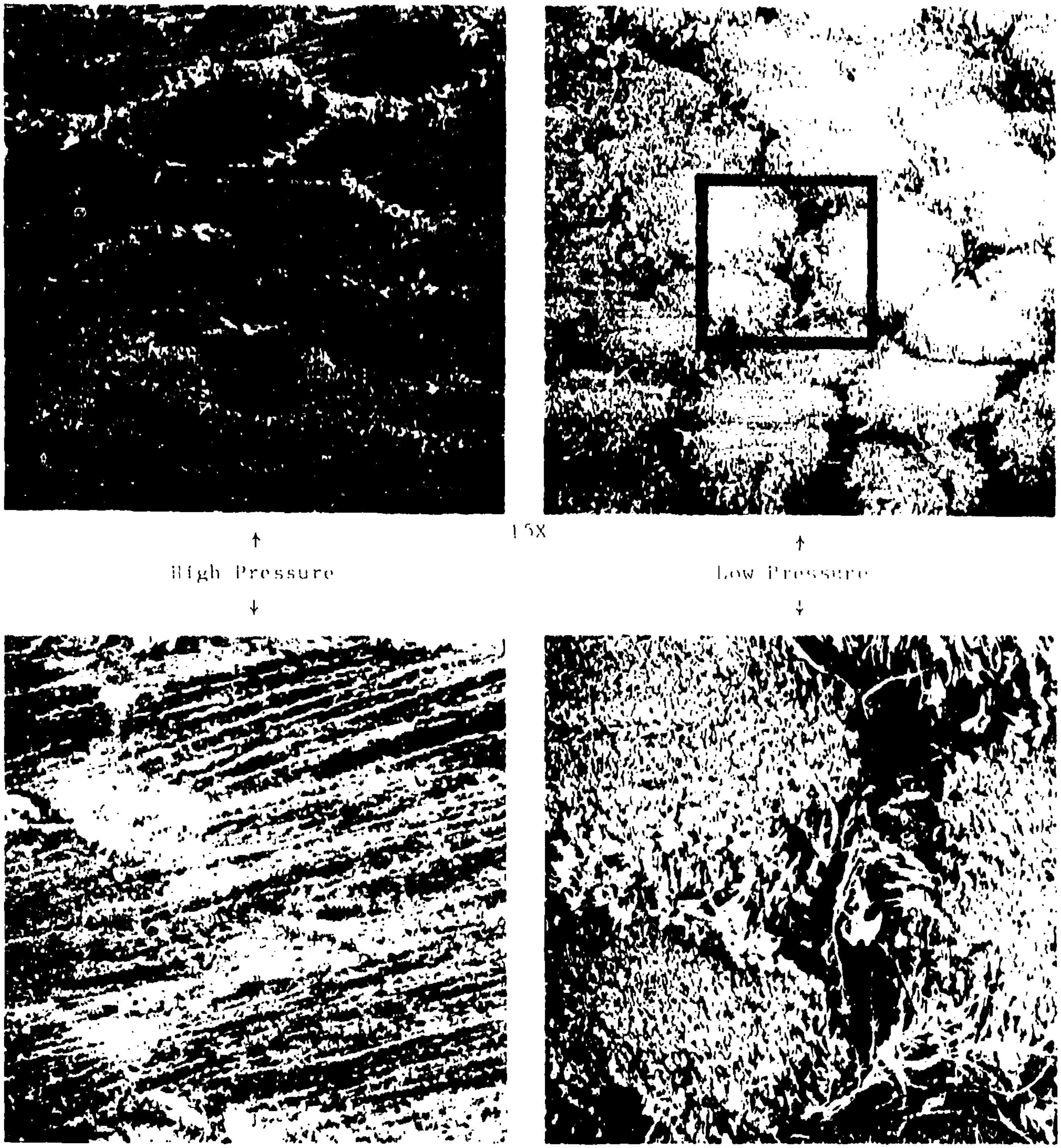

Figure 4. Enlarged cross-sections of high and low pressure laminated Kevlar (R) fabric bonded with 28 percent modified phenolic resin.

was 15 to 18 percent, which increased at a later date to 18 to 21 percent. As a result of studies of nylon fabric and laminated panels, it was assumed that high and low-pressure, fabricated, nylon-reinforced structures would provide similar ballistic resistance properties. This conclusion seemed to be substantiated by successful prediction of the ballistic resistance,[9] in terms of V_{50},* of the low-pressure fabricated CVC Helmet from the performance characteristics of the high-pressure molded helmet liner.

It is now known that the melt characteristics of nylon are self-limiting in resisting penetration. Since Kevlar(R) does not melt, the extension characteristics can be fully utilized to dissipate kinetic energy. For Kevlar(R) laminates there is a difference in ballistic penetration resistance capability between high and low pressure laminations. Table 6 shows that resin concentration should not significantly affect the V_{50} ballistic limit at a given pressure (less than 100 feet per second differences). Tables 6 and 7 indicate, however, that the V_{50} ballistic limit of low pressure laminates are about 10 percent greater than the high pressure laminates.

TABLE 6. Ballistic Limit (V_{50}) of Laminated Panels Made from 9 Plies Kevlar(R) Fabric Bonded with Different Resin Concentrations at High and Low Pressures

Contractor's Estimate (%)	High Pressure Resin Coated (%)	High Pressure V-50 fps	Low Pressure Resin Coated (%)	Low Pressure V-50 fps
15.8	17.8	1271	15.7	1388
19.8	20.3	1247	18.4	1407
28.9	27.4	1243	28.6	1311
43.6	20.7	1320	40.6	1359
50.2	22.9		46.6	1342

TABLE 7. Ballistic Limit (V_{50}) of Kevlar(R) Fabric Panels Bonded with a Nominal 20 Percent Modified Phenolic Resin Content at High and Low Pressures

	V_{50} Ballistic Limit - Feet Per Second Plies of Fabric			
	9	10	11	12
High Press.	1247	1332	1385	1454
Low Press.	1407	1460	--	1623

*V_{50} ballistic limit is the impact velocity at which the probability of penetration of a material by a test projectile is 50 percent.

CONCLUSIONS

Panels made from a run of coated Kevlar(R) fabric differing only in laminating pressures exhibited markedly different performance characteristics. The low-pressure laminate, though thicker than the high-pressure laminate, was more flexible, absorbed more flexural energy, and had greater resistance to ballistic penetration. Table 8 summarizes the characteristics of high and low-pressure laminates, each made from 9 plies of 28.9% resin content coated fabric and having comparable resin content.

TABLE 8. Properties of Kevlar(R) Fabric Panels Made by High and Low Laminating Pressures

	High Pressure	Low Pressure
Resin Content (%)	27.4	28.6
Thickness (in.)	0.171	0.204
Flexural Modulus (x 10^5 psi)	25.60	12.37
Energy Absorbed (in.-lbs/in^2)	214.9	158.2
Hardness (Rockwell L)	104.2	55.4
V_{50} Ballistic Resistance (fps)	1243	1311

Although the coated Kevlar(R) fabric is often called a "prepreg", it is coated with resin and not impregnated with resin. Low pressure lamination maintained this configuration where the resin coating served as bonding medium for the layers of fabric. Under high pressure, the resin was forced into the voids between the yarns and fibers, forming them into a "solid" mass. Electron micrographs (Fig. 4) graphically show the compacted, resin filled structure of the high-pressure lamination and the bonded layers of fabric of the low-pressure laminate. Each fiber of the high-pressure panel appears to be encapsulated in resin, thereby imparting rigidity and reducing its extensibility. The high flexural modulus of the high-pressure laminates may be attributed to the interstitial bonding of fibers, yarns, and plies of fabric with the crosslinked modified phenolic resin. The low-pressure panels are formed by bonding the surfaces of each layer of fabric to its adjacent plies. The voids between the fibers and yarns permit some freedom of movement and elongation, thereby providing those elements that result in a flexible structure.

Those properties that impart flexibility or rigidity to the panels are the same properties that influence the ballistic penetration characteristics. The freedom of movement of the yarns and individual fibers of the low-pressure structure permits the energy absorption mechanisms of Kevlar(R) fabric to be utilized. Energy of a ballistic impact will be absorbed by a concerted action of deflection, elongation,[10] and fracture (or delamination) of the bond between

of fabric. Unlike the low-pressure laminated panels, the high-pressure laminates exhibited a lesser resistance to ballistic penetration. The resin-saturated structure with encapsulated or restrained yarns and fibers were possibly subjected to a shear phenomenon, thereby not utilizing the high tenacity characteristics of the Kevlar(R) to absorb impact energy.

Nothing in this study contraindicates the concepts that processing ballistic structures from Kevlar(R) fabric is different than the fabrication technology used to fabricate laminated nylon fabric for helmets.

Low-pressure laminates from Kevlar(R) fabric bonded with catalyzed and modified phenolic resin are more flexible and dissipate or absorb more flexural and ballistic energy than equivalent (resin content) high-pressure laminates.

This document reports research undertaken at the US Army Natick Research and Development Command and has been assigned No. NATICK/TR-84/030 in the series of reports approved for publication.

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APPENDIX

Mr. Frank Figucia, Materials Research and Engineering Division, Individual Protection Laboratory, Natick R&D Center, is concerned with the mechanics of energy absorption and penetration mechanics of textile materials. He examined the ballistic data and ensuing discussion and offered the following:

Ballistic energy absorptive trends in Figure A-1 show that neither high nor low-pressure laminates are as efficient as unlaminated layers of fabric (without resin additive). This result could be predicted based on the greater weight of the added resin, and the fact that the resin contributes little or nothing to resisting the penetration mechanisms.

Since the resin contributes nothing to the ballistic penetration resistance, the efficiency of laminates is determined based only on the mass of the fabric component. Figure A-2 shows that under low-pressure lamination, the fabric component responds similarly to uncoated plied fabric. Under high-pressure lamination, however, the ballistic energy absorption is significantly reduced. This indicates that resin bonding could inhibit the normal fabric response mechanisms to ballistic impact, but with proper processing the response mechanism need not be adversely affected.

The results of the study of resin concentration and laminating pressure on Kevlar(R) fabric systems suggest continued studies to identify basic mechanistic changes and their relationship with resin concentrations and laminating pressures.

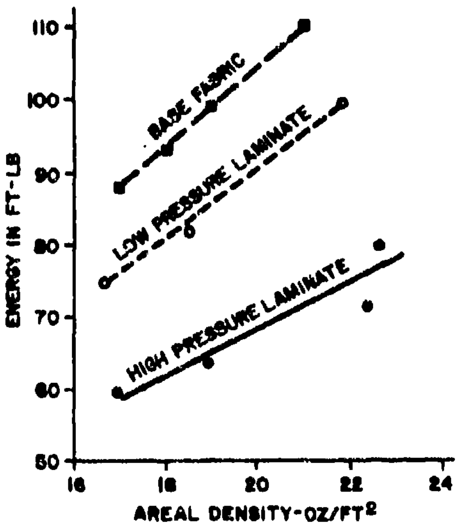

FIGURE A1. ENERGY ABSORBED BY KEVLAR® PANELS AS A FUNCTION OF THEIR AREAL DENSITY

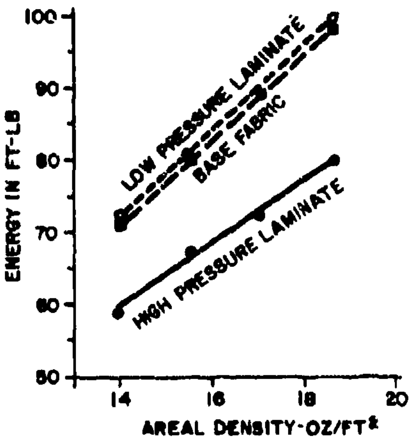

FIGURE A2. ENERGY ABSORBED BY KEVLAR® PANELS AS A FUNCTION OF THE AREAL DENSITY OF THEIR BASE FABRIC